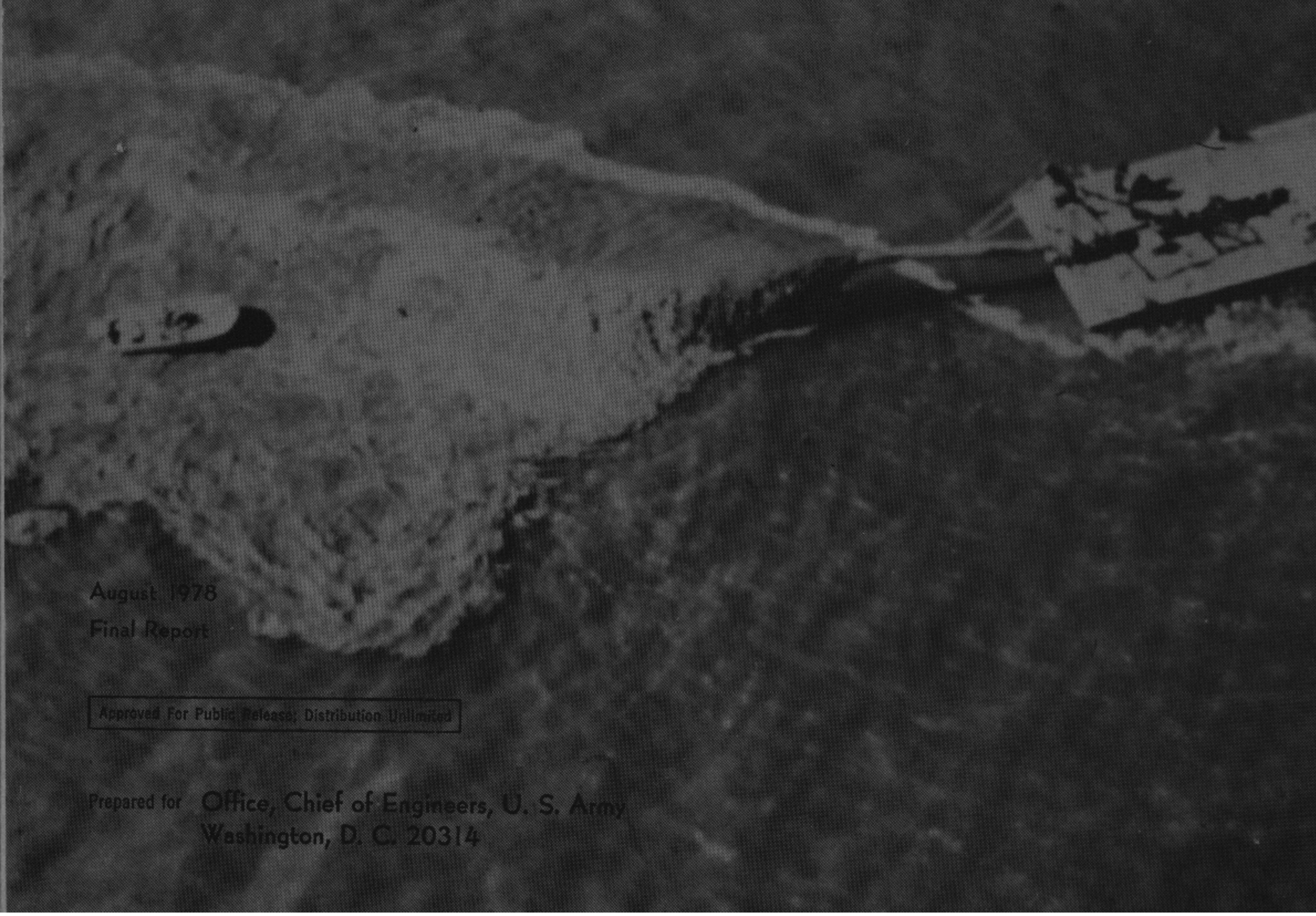
SYNTHESIS OF RESEARCH RESULTS

DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT DS-78-13

PREDICTION AND CONTROL OF DREDGED MATERIAL DISPERSION AROUND DREDGING AND OPEN-WATER PIPELINE DISPOSAL OPERATIONS



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Final Report

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THE DMRP SYNTHESIS REPORT SERIES

Technical Report No.	Title
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In response to the concern over the potential impact of dredged material dispersion, Task 6C of the Dredged Material Research Program was established to develop the capability for predicting the nature, degree, and extent of dredged material dispersion in the vicinity of dredging and open-water pipeline disposal operations. In addition, methods for controlling this dispersion were evaluated. This report synthesizes the results of eight contract research studies and

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20. ABSTRACT (Continued).

summarizes the available literature concerned with turbidity generation by different types of dredging operations.

Water-column turbidity generated by dredging operations is usually restricted to the vicinity of the operation and decreases rapidly with increasing distance from the operation due to settling and horizontal dispersion of the suspended material. Turbidity levels around dredging operations can be reduced by improving existing cutterhead dredging equipment and operational techniques, using watertight buckets, and eliminating hopper dredge overflow or using a submerged overflow system.

During open-water pipeline disposal of fine-grained dredged material slurry, 97 to 99 percent of the material descends rapidly to the bottom of the disposal area where it forms a low gradient fluid mud mound. Suspended solids concentrations within the fluid mud layer increase with depth from 10 g/ℓ at the water column/fluid mud interface to levels of 300 to 500 g/ℓ at the bottom of the layer. One to three percent of the discharged slurry will remain suspended in the water column in the form of a turbidity plume. Average plume concentrations of several hundred milligrams per litre decrease rapidly with distance downstream from the discharge point and laterally away from the plume center line due to settling and horizontal dispersion.

The relative degree of dredged material dispersion at open-water pipeline disposal operations can be best controlled by using different discharge configurations. Water-column turbidity can be all but eliminated by using a submerged diffuser system at the end of the pipeline. The dispersion of near-surface turbidity can often be controlled to a certain extent by placing a silt curtain downstream or around certain types of dredging/disposal operations located in quiescent environments where current velocities are less than 50 cm/sec.

Although the impacts associated with existing dredging and disposal operations are not as severe as previously alleged, by implementing the guidelines given in this report for selecting dredges, improving operational techniques, properly using silt curtains, and selecting appropriate pipeline discharge configurations, any dredging or disposal operation can be conditioned to minimize its environmental impact.

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SUMMARY

In response to concern over the potential impact of dredged material that may be suspended and dispersed during dredging and disposal operations and the aesthetically displeasing appearance of near-surface turbidity plumes, one task within the Dredged Material Research Program was established to develop the capability for predicting the nature, degree, and extent of suspended dredged material in the vicinity of dredging and open-water pipeline disposal operations. Furthermore, the program set out to evaluate methods for controlling the dispersion of dredged material when necessary. This report synthesizes the laboratory and field results of eight separate, but related, contract research studies performed within this task and summarizes the available literature concerned with turbidity generation by different types of dredging operations.

Water-column turbidity generated by dredging operations involving fine-grained material is usually restricted to the vicinity of the operation and decreases rapidly with increasing distance from the operation. Maximum concentrations of suspended solids within 500 m of a clamshell operation will probably be less than 500 mg/ℓ, with average concentrations of approximately 100 mg/ℓ. Elevated levels of suspended solids around cutterhead dredges are restricted to the immediate vicinity of the cutter, where concentrations may be as high as a few tens of grams per litre within 3 m of the cutter. Near-bottom levels of a few hundred milligrams per litre may be found within a few hundred metres of the cutter. Hopper dredges without overflow may generate near-bottom suspended solids concentrations of a few grams per litre near the draghead(s). During overflow operations, turbidity plumes with average concentrations of several hundred milligrams per litre may extend behind the dredge for distances up to 1200 m. Turbidity levels around dredging operations can be reduced when necessary, but not without appreciable cost, by improving existing cutterhead dredging equipment rational techniques, using watertight buckets and eliminating hopper dredge overflow, or using a submerged overflow system. Unconventional dredging

systems such as the Mud Cat, Waterless dredge, Delta dredge, pneumatic pumping systems, or the Clean Up system may provide some advantage on certain types of environmentally sensitive dredging operations.

During open-water disposal of fine-grained dredged material slurry generated by pipeline dredge operations, an estimated 97 to 99 percent of the slurry descends rapidly to the bottom of the disposal area. Where bottom slopes are greater than 0.75 deg (1:76), the resulting fluid mud will in most cases flow downslope as long as that slope is maintained. On nonsloping bottoms, the fluid mud will accumulate in the form of a fluid mud mound with average slopes of 1:500. Suspended solids concentrations within the fluid mud layer increase with depth from 10 g/ℓ at the water column/fluid mud interface to levels of 300 to 500 g/ℓ at the bottom of the layer. One to three percent of the discharged slurry will not descend rapidly to the bottom, but will remain suspended in the water column in the form of a turbidity plume. Average plume concentrations of several hundred milligrams per litre decrease rapidly with distance downstream from the discharge point and laterally away from the plume center line due to settling and horizontal dispersion.

The dispersion of dredged material at open-water pipeline disposal operations can be controlled best by using different discharge configurations. The simple open-ended pipeline, discharging above and parallel to the water surface, will maximize the dispersion of the slurry throughout the water column and produce a relatively thin, but widespread, fluid mud layer. In water depths in excess of 2 m, the dispersion of the material in the water column can be decreased by vertically discharging the slurry through a 90-deg elbow at a depth of 0.5 to 1 m below the water surface. Most water-column turbidity can be eliminated by using a submerged diffuser system at the end of the pipeline. This latter discharge configuration also maximizes the mounding tendency of the fluid mud dredged material, thereby minimizing its areal coverage over the disposal area.

The dispersion of near-surface turbidity can be controlled, to a certain extent, by placing a silt curtain downstream or around certain types of dredging/disposal operations. Under quiescent current conditions (less than 5 cm/sec) turbidity levels in the water column outside the curtain may be reduced by as much as 80 to 90 percent; however, the effectiveness of silt curtains decreases with increasing current velocity. Silt curtains are not recommended where currents exceed 50 cm/sec (1 knot).

Since dredging/disposal projects should be evaluated on a case-by-case basis, it is imperative to concurrently consider all components of the operation, including excavation, transportation, and disposal of the material as a total integrated system. The best dredging system may not be compatible with the best disposal system. In addition, the impact of each component of the system must be objectively evaluated with respect to the cost and overall benefits of the operation.

PREFACE

This report synthesizes the results of eight research studies within Task 6C, entitled "Turbidity Prediction and Control," of the Disposal Operations Project (DOP), Dredged Material Research Program (DMRP). Planning and management of Task 6C as well as the preparation of this report were performed by Dr. William D. Barnard under the general supervision of Mr. Charles C. Calhoun, Jr., manager of the DOP; Dr. Roger T. Saucier, Special Assistant for Dredged Material Research; and Dr. John Harrison, Chief, Environmental Laboratory. The Task 6C research synthesized in this report was performed by private engineering firms and universities under contract to the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

Commander and Director of WES during the preparation of this report was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, METRIC (SI) TO U. S. CUSTOMARY UNITS OF MEASUREMENT

Metric (SI) units of measurement used in this report can be converted to U. S. customary units as follows:

Multiply	By	To Obtain
centimetres	0.3937	inches
centimetres per second	0.3937	inches per second
cubic centimetres	0.610	cubic inches
cubic metres	1.308	cubic yards
cubic metres	35.31	cubic feet
cubic metres per hour	1.308	cubic yards per hour
grams	0.03527	ounces
grams per cubic centimetre	0.03613	pounds per cubic inch
grams per litre	3.61273	pounds per cubic inch
grams per second	2.205×10^{-3}	pounds per second
grams per square metre	0.02949	ounces per square yard
kilograms	2.2046	pounds
kilograms per metre	0.6720	pounds per foot
kilometres	3281.0	feet
litres	0.2642	gallons
metres	3.2808	feet
metres per second	3.2808	feet per second
milligrams per cubic centimetre	0.03613×10^{-3}	pounds per cubic inch
milligrams per litre	0.00361273	pounds per cubic inch
milligrams per second	0.03527×10^{-3}	ounces per second
millimetres	0.03937	inches
newtons	0.2248089	pounds (force)
newtons per metre	0.0057101	pounds (force) per inch
square centimetres	0.1550	square inches
square metres	1.196	square yards

PART I: INTRODUCTION

Background

1. One of the major concerns about dredging and open-water disposal operations involves the possible environmental impact associated with the resuspension and subsequent dispersion of fine-grained dredged material. This concern is particularly significant considering the fact that the vast majority of the potentially toxic chemical contaminants present in bottom sediments is associated with the fine-grained fraction that is most susceptible to dispersion.[1] However, evaluating the fate of resuspended dredged material is not a simple task, especially when dealing with fine-grained (silt and clay) slurries generated by maintenance dredging operations. In addition, regardless of the degree of dredged material dispersion, under certain environmentally and/or aesthetically sensitive circumstances, control of this dispersion may be advisable.

Task 6C Research

2. Task 6C of the DMRP,[2] entitled "Turbidity Prediction and Control," was established to develop the capability for predicting the nature, degree, and extent of suspended dredged material in the vicinity of open-water pipeline disposal operations. In addition, several studies evaluated physical and chemical methods for controlling the dispersion of dredged material slurry in the vicinity of both dredging and disposal operations. The biological and chemical impacts were evaluated under related DMRP Tasks 1A (Aquatic Disposal Field Investigations),[3] 1C (Effects of Dredging and Disposal on Water Quality),[4] 1D (Effects of Dredging and Disposal on Aquatic Organisms),[5] and 1E (Pollution Status of Dredged Material).[6] Hopper dredge and barge disposal of dredged material were evaluated under Task 1B (Movements of Dredged Material).[7]

3. The eight studies comprising Task 6C are listed in Table 1. In addition to synthesizing the results of these research efforts, this report also summarizes the available literature related to turbidity generation by different types of dredging operations and describes some of the dredging equipment that has been developed to minimize the dispersion of dredged sediment. The nonavailability of much of this specialized equipment in the United States and the scope of this project did not permit testing or comparison of the capabilities or turbidity reduction potential of any of this equipment.

4. This study addressed the major problems associated with dredged material dispersion. Because of the high degree of variability associated with different environmental and operational parameters, many phenomena associated with dredged material dispersion can only be described qualitatively at this time, based on an integration and interpretation of both laboratory and field observations. Quantitative, emmpirical predictions are given whenever possible based on "worst" case situations; however, these estimates may be revised in the future as more data are collected and understanding of the controlling processes increases.

Types of Dredged Material Suspensions

5. Field and laboratory studies concerned with the dispersion of dredged material indicate that sediment resuspended during dredging or open-water disposal either remains suspended in the upper water column at relatively low concentrations or forms high concentration suspensions that cover the bottom. The material suspended in the water column is often referred to as turbidity; the dense near-bottom suspensions are commonly called fluid mud or fluff. Because these terms are often misused and confusing, they will be defined and discussed in greater detail in the following paragraphs.

6. Dredged material suspensions are quantitatively classified and/or described by their concentration of suspended solids expressed in milligrams or grams per litre (mg/ℓ or g/ℓ), percent solids (by weight),

Table 1

Task 6C Research Studies

Research Study	Contractor	Objective
	Prediction of Dredged Material Dispersion	
Turbidity Research		
Laboratory Study Related to Predicting the Turbidity-Generation Potential of Sediments to be Dredged	Walden Research Division of ABCOR, Inc. Wilmington, Mass. (Mr. Barry A. Wechsler and Dr. David R. Cogley)	To determine the amount of turbidity that a given sediment is likely to produce when subjected to a dredging operation by evaluating those sedimentary/hydrologic factors causing and/or controlling turbidity.
Field Investigation of the Nature, Degree, and Extent of Turbidity Generated by Open-Water Pipeline Disposal Operations	State University of N. Y. at Stony Brook Stony Brook, N. Y. (Drs. J. R. Schubel and H. H. Carter)	To investigate the nature, degree, and three-dimensional extent of plumes of suspended solids and associated dissolved chemical constituents generated by open-water pipeline disposal operations.
Fluid Mud Research		
Field Study of Fluid Mud Dredged Material: Its Physical Nature and Dispersion	Virginia Institute of Marine Science Gloucester Pt., Va. (Drs. Maynard M. Nichols and Richard W. Faas)	To determine the significance of fluid mud in the dispersal of dredged material and in generating turbidity at dredging and disposal operations by measuring the nature, extent, and thickness of fluid mud layers with respect to their source, hydrologic parameters, and behavior as a function of time.
Laboratory Investigation of the Dynamics of Mudflows Generated by Open-Water Pipeline Disposal Operations	JBF Scientific Corp. Wilmington, Mass. (Mr. George Henry)	To improve the basic understanding of the dynamics of fluid mud dispersion by evaluating possible controlling factors such as sediment composition, bottom slope and roughness, discharge velocity, salinity, and currents and waves.
	Control of Dredged Material Dispersion	
Investigation of Techniques for Reducing Turbidity Associated with Present Dredging Procedures and Operations	John Huston, Inc. Corpus Christi, Tex. (Mr. John Huston)	To evaluate new and existing operational techniques with respect to their turbidity-reduction potential, cost, effect on production, and ease of implementation.
Analysis of the Functional Capabilities and Performance of Silt Curtains	JBF Scientific Corporation Wilmington, Mass. (Mr. Edward E. Johanson)	To inventory silt curtain specifications, evaluate deployment methods and systems, and determine silt curtain effectiveness as it relates to factors such as size, shape, and design of the enclosed area; the curtain material used; the sediment being dredged; and limiting environmental conditions.
Evaluation of the Submerged Discharge of Dredged Material Slurry During Pipeline Dredge Operations	JBF Scientific Corporation Wilmington, Mass. (Mr. Robert W. Neal and Mr. George Henry)	To evaluate the technical, operational, and economic feasibility of using submerged pipeline discharge of dredged material slurry as one disposal alternative within a designated open-water disposal area to minimize the dispersion of the dredged material slurry into the water column.
Assessment of Chemical Flocculants and Friction-Reducing Agents for Application in Dredging and Dredged Material Disposal	Mississippi State University Starkville, Miss. (Dr. Donald O. Hill)	To perform a state-of-the-art review and assessment of the potential utilization of flocculants for turbidity control in dredging and disposal operations and friction-reducing (wetting) agents for increasing the efficiency of the pipeline transport of dredged material slurry.

or bulk density. Relatively low levels of suspended solids characteristic of turbidity plumes are expressed in milligrams per litre or grams per litre indicating the weight of dry solids in a litre volume of sample. Intermediate levels of suspended solids characteristic of dredged material slurry and fluid muds are usually given in grams per litre or percent solids by weight. Percent solids by weight is calculated by dividing the dry weight of solids in a sample by the total weight of the sample (including both the solids plus water) and converting the fraction to a percentage. Bottom sediments with relatively high solids content are usually described in terms of bulk density or the wet weight of a volume of sediment. Units of bulk density are in grams per cubic centimetre. Appendix A shows the relationship between the three methods of expressing solids content.

7. In contrast to the above system, dredgers usually describe a slurry in terms of percent solids by volume where the volume of in situ sediment (including both the solids plus water) excavated during an operation is divided by the volume of slurry pumped; this fraction is then converted to a percentage. In some instances, percent solids is based on apparent volume where the volume of settled solids in a container is divided by the total volume of the settled solids plus the water in the container. In most cases this latter percentage provides an erroneous indication of the solids content, as described by dredgers, since the bulk density of the settled sediment will normally be less than its in situ bulk density before dredging.

Water-column turbidity

8. Turbidity is commonly used to describe the cloudy or muddy appearance of water. In the strictest sense, turbidity describes an optical property of a particular liquid medium, in this case water, that causes light to be scattered and absorbed rather than transmitted through the water. Scattering and absorption are caused by the dissolved and suspended organic and inorganic substances in the water. The amount of scattering and absorption is controlled by the concentration of suspended particles as well as their shape, size distribution, refractive index, color, and absorption spectra.[8]

9. In addition to the varied definitions of turbidity, there are also many techniques and instruments (turbidimeters) that have been and are used to evaluate or "quantify" turbidity.[9] Turbidity measurements were originally made in the early 1900's with the Jackson candle turbidimeter, calibrated in Jackson Turbidity Units (JTU's) or Jackson Candle Units (JCU's), to approximate the concentration of suspended solids in terms of parts per million (ppm) of a suspension of Fuller's or diatomaceous earth. Turbidimeters were later calibrated with Formazin, a solution of hydrazine sulfate and hexamethylenetetramine, in terms of Formazin Turbidity Units (FTU's). The Jackson candle meter has been replaced by a myriad of turbidimeters that usually measure turbidity in terms of light transmission (transmissometers) or scattering (nephelometers) where the amount of light that is transmitted through or scattered by a particular sample is measured relative to the initial intensity of a light beam. Nephelometers are often calibrated using a scale of Nephelometric Turbidity Units (NTU's). Unfortunately, suspensions of different types of material with the same turbidity reading (in FTU's, NTU's, or JTU's) may have similar optical properties, but do not necessarily contain the same concentration of suspended solids. Furthermore, different types of turbidimeters, although calibrated with the same standard suspension, may indicate different turbidity levels for the same sample.[10]

10. The turbidity levels of water samples collected around dredging and disposal operations for all of the 6C research studies were quantitatively evaluated with turbidimeters or by measuring the concentration of suspended material in water samples. By simultaneously measuring both the turbidity and concentration of total suspended solids over a range of values, a correlation curve was developed showing the relationship (which may not necessarily be linear) between turbidity (expressed in NTU's, FTU's, JTU's, or percent transmission) and total suspended solids. Using an empirical correlation curve for each field site, all the turbidity readings were converted to levels of total suspended solids. These levels were then used to compare suspended solids concentrations at different locations. All turbidity levels in this

report are therefore expressed in terms of milligrams or grams per litre.

11. The turbidity plumes generated by dredging and disposal operations are usually caused by low concentrations of silt and clay-size particles (with diameters of less than 0.03 mm)* or small flocs (i.e., masses of agglomerated particles) that settle independently at very slow rates through the water column. Although solids concentrations in the upper water column in the vicinity of dredging and disposal operations usually do not exceed several hundred milligrams per litre, the particles/flocs continue to settle independently until the solids concentration near the bottom exceeds approximately 10 g/ℓ.[11,12] Therefore, in this discussion, the term turbidity will be used to describe suspensions in the water column where the solids concentration ranges from 0 to 10 g/ℓ (Table 2). Factors controlling the settling rates of these

Table 2

DREDGED MATERIAL SUSPENSIONS

QUALITATIVE DESCRIPTOR	PROCESSES		SOLIDS CONCENTRATION (g/ℓ) AVERAGE	(RANGE)	BULK DENSITY (g/cc)* AVERAGE CENTER	(RANGE)
			0 g/ℓ		1.000	
TURBIDITY	SEDIMENTATION	INDEPENDENT SETTLING				
		/////	10 g/ℓ	(5-20)	1.006	(1.003-1.012)
LOW DENSITY		HINDERED OR ZONE SETTLING				
FLUID MUD		/////	200 g/ℓ	(175-225)	1.125	(1.109-1.140)
HIGH DENSITY						
"TYPICAL" BOTTOM SEDIMENT	SELF-WEIGHT CONSOLIDATION		400 g/ℓ	(300-500)	1.249	(1.187–1.311)

*ASSUME SOLIDS = 2.65 g/cc AND WATER = 1.00 g/cc

* For convenience, factors for converting the metric (SI) to U. S. customary units of measurement are given on page 12.

particles, which in turn directly affect the characteristics of turbidity plumes, are discussed in Part III.

Fluid mud dredged material

12. Naturally occuring fine-grained sediment that accumulates in rivers, estuaries, and dredged channels as well as dredge-induced near-bottom suspensions of dredged material slurry often form layers of fluid mud overlying more dense bottom sediment.[13] Since there is no universally accepted definition of fluid mud, in this report fluid mud has been classified as low- or high-density fluid mud, based on its solids concentration. The solids concentration marking the transition zones between turbid water, low- and high-density fluid mud, and "typical" bottom sediment varies depending on the texture and composition of the dredged material suspension. Table 2 gives typical average values and ranges associated with each transition zone.

13. Low-density fluid mud. The concentration of suspended solids in a turbidity plume generally increases exponentially with depth. At the relatively well-defined interface between turbid water and the surface of the fluid mud layer, the solids concentration increases very rapidly to levels of several tens of grams per litre. This turbid water/fluid mud interface is approximated by a concentration of 10 g/ℓ, although the exact concentration may vary from 5 to 20 g/ℓ. Low-density fluid mud is characterized by randomly oriented particles or flocs that settle at "hindered" rates; the fluid mud layer settles as a mass as the interstitial water (between the particles) migrates upwards toward the surface of the mud layer. This sedimentation process is called "hindered" or "zone" settling.[11] Low-density fluid mud may be stationary or may freely flow outward, away from the discharge point of an open-water pipeline disposal operation, like syrup poured on a platter, or downslope as a mudflow. At solids concentrations of 175 to 225 g/ℓ the hindered settling process apparently ends and self-weight consolidation begins.[11,12,14] Therefore, an approximate solids concentration of 200 g/ℓ generally indicates the transition zone between low- and high-density fluid mud.

14. High-density fluid mud. When the solids concentration within the fluid mud layer exceeds 200 g/ℓ, the degree of particle contact increases. Because of the high solids concentration and this high degree of particle interaction, high-density fluid mud possesses a certain degree of rigidity and will not normally flow freely as low-density fluid mud may.[12] During this process, the interstitial water is squeezed out under the weight of the overlying material, the bulk density of the material increases, and the randomly oriented particle structure and/or flocs probably begin to break down.[11] Although this high-density fluid mud does not flow freely, it may be subject to sudden failure or creeping.

Factors Controlling Dredged Material Dispersion

15. The nature, degree, and extent of dredged material dispersion around a dredging or disposal operation are controlled by many factors, including: the characteristics of the dredged material, such as its size distribution, solids concentration, and composition; the nature of the dredging or disposal operation, such as dredge type and size, discharge/cutter configuration, discharge rate, solids concentration of the slurry, and the operational procedures being used; and the characteristics of the hydrologic regime in the vicinity of the operation, including salinity and hydrodynamic forces (i.e., waves, currents, etc.). The relative importance of the different factors may vary significantly from site to site. These factors are discussed in more detail in subsequent chapters of this report dealing with the dispersion of dredged material at dredging and open-water pipeline disposal operations (in that order).

PART II: PREDICTION AND CONTROL OF TURBIDITY: DREDGING OPERATIONS

16. Under a given set of environmental conditions, different types of dredges will generate different levels of turbidity. While the dredging equipment certainly has a large effect on the amount and concentration of sediment that is resuspended, the techniques for operating this equipment are also important. Although operator training and performance may be one of the most important factors controlling turbidity generation, it is often difficult to evaluate the various parameters of a dredge's operation that reflect the skills of the operator. Unfortunately, in most of the literature cited in this chapter, turbidity levels were measured with little regard to the operation of the dredges or their rates of production (i.e., cubic metres of material dredged per hour).

17. With this in mind, the following discussion examines the levels of turbidity generated by different types of conventional dredges as well as possible methods for minimizing the generation of turbidity by modifying existing equipment and operational procedures. This discussion also includes a brief description of an improved overflow system for hopper dredges, watertight clamshell buckets, and several unconventional dredges that are not widely used in the United States, but appear to have some potential for minimizing turbidity generation.

Grab/Bucket/Clamshell Dredges

18. The grab, bucket, or clamshell dredge consists of a bucket or clamshell operated from a crane or derrick mounted on a barge.[15] It is used extensively for removing relatively small volumes of material (i.e., a few tens or hundreds of thousands of cubic metres) particularly around docks and piers or within other restricted areas. The sediment is removed at nearly its in situ density; however, production rates (relative to a cutterhead dredge) are low, especially in consolidated material. The material is usually placed in barges or scows for transportation to the disposal area. Although the dredging depth is

practically unlimited, the deeper the depth the lower the production rate. In addition, the clamshell dredge usually leaves an irregular, cratered bottom.

Sources of turbidity

19. The turbidity generated by a typical clamshell operation can be traced to four major sources. Most of this turbidity is the result of sediment resuspension occurring when the bucket impacts on and is pulled off the bottom. Also, because most buckets are not covered, the "surface" material in the bucket and the material adhering to the outside of the bucket are exposed to the water column as the bucket is pulled up through the water column. When the bucket breaks the water surface, turbid water may spill out of the bucket or may leak through openings between the jaws. In addition to inadvertent spillage of material during the barge loading operation, turbid water in the barges is often intentionally overflowed (i.e., displaced by higher density material) to increase the barge's effective load.

Field measurements

20. There is a great deal of variability in the amount of material resuspended by clamshell dredges due to variations in bucket sizes, operating conditions, sediment types, and hydrodynamic conditions at the dredging site.

a. During a channel deepening project using a 16.5-cu m bucket in San Francisco Bay, California, turbidity levels in the water column 50 m downstream from the operation were generally less than 200 mg/ℓ and averaged 30 to 90 mg/ℓ relative to background levels outside the plume of approximately 40 mg/ℓ. Suspended solid levels decreased with increasing distance from the dredging operation due to dilution and settling of the suspended material. The visible plume was about 300 m long at the surface and approximately 450 m long at a bottom depth of 10 m.[16]

b. During a "new work" channel deepening operation on the lower Thames River, Connecticut, maximum suspended solids concentrations of 68, 110, and 168 mg/ℓ at the surface, middepth (3 m), and near bottom (10 m), respectively, were noted within 100 m downstream of a 12.8-cu m clamshell dredging and barge loading operation. These maximum concentrations decreased very rapidly to background levels of 5 mg/ℓ within 300 m at the surface and 500 m near the bottom.[17]

c. Suspended solids levels 22 m downstream from a 16.5-cu m clamshell operation performing maintenance work in the Brewerton Cut-Off Angle, Patapsco River, Maryland, were about 30 mg/ℓ at near-bottom depths of 10 m relative to background water column suspended solids concentrations of approximately 10 mg/ℓ or less. These higher near-bottom concentrations persisted for about 90 m downstream from the dredge, whereas visual surface traces usually persisted for less than 460 m.[18]

d. According to Japanese measurements made in the vicinity of a 1-cu m clamshell operation dredging fine-grained material from a depth of 3.5 m, maximum suspended solids concentrations in the water column 7 m downstream from the dredging operation ranged from 150 to 300 mg/ℓ relative to background levels of less than 30 mg/ℓ.* These levels decreased by about 50 percent at a distance of 23 m. Generally speaking, the turbidity levels in the upper water column were usually somewhat less than those levels at middepth or near the bottom.[19]

21. Based on these limited measurements, it appears that, depending on current velocities, the turbidity plume downstream of a typical clamshell operation may extend approximately 300 m at the surface and 500 m near the bottom. Maximum concentrations of suspended solids in the surface plume should be less than 500 mg/ℓ in the immediate vicinity of the operation and decrease rapidly with distance from the operation due to settling and dilution of the material. Average water-column concentrations should generally be less than 100 mg/ℓ. The near-bottom plume will probably have a higher solids concentration, indicating that resuspension of bottom material near the clamshell impact point is probably the primary source of turbidity in the lower water column. The visible near-surface plume will probably dissipate rapidly within an hour or two after the operation ceases.

* These suspended solids concentrations are unverified estimates based on a conversion of turbidity to milligrams per litre (Figure 3.14, Yagi et al.[19]) from a different test site in Japan.

Turbidity control using watertight buckets

22. To minimize the turbidity generated by a typical clamshell operation, the Port and Harbor Research Institute, Japan, developed a watertight bucket with edges that seal when the bucket is closed (Figure 1). In addition, the top of the watertight bucket is covered so

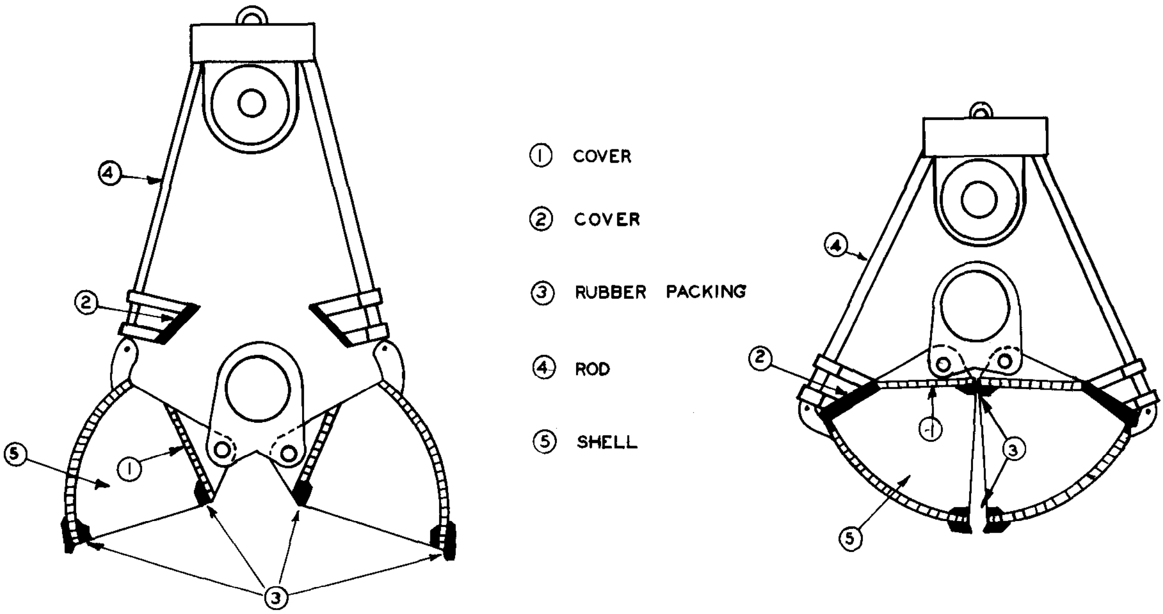

Figure 1. Open and closed positions of the watertight bucket

that the dredged material is totally enclosed within the bucket. Available sizes range from 2 to 20 cu m. According to the manufacturer, Mitsubishi Seiko Company, Ltd. (Box 48, Nippon Building, 2-6-2 Otemachi, Chiyoda-ku, Tokyo, Japan), these buckets are best adapted for dredging fine-grained, soft mud.

23. A direct comparison of 1-cu m typical and watertight clamshell operations indicates that watertight buckets generate 30 to 70 percent less turbidity in the water column than the typical buckets. This reduction is probably due primarily to the fact that leakage of dredged material from watertight buckets is reduced by approximately 35 percent.[19] Other measurements made approximately 10 m downstream from a 4-cu m watertight clamshell dredge excavating fine-grained material from a depth of 8 m indicated that maximum suspended solids

concentrations were approximately 500 mg/ℓ or less throughout the water column relative to background levels of 50 mg/ℓ or less. Turbidity levels decreased very rapidly with increasing distance from the operation and approached background levels several tens of metres downstream from the dredge.[20] Near-bottom and midwater column suspended solids levels were greater than surface levels,[19,20] indicating that resuspension of bottom material near the clamshell impact point is probably responsible for most of the material suspended in the lower portion of the water column.

Cutterhead Dredges

24. The cutterhead dredge (Figure 2) is the most commonly used dredge in the United States. With this type of dredge a rotating

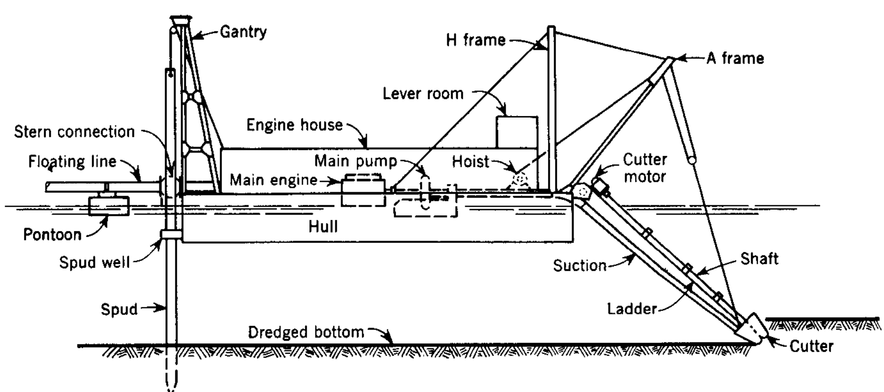

Figure 2. Typical cutterhead dredge (Reprinted by permission from Hydraulic Dredging, by J. W. Huston, 1970. Cornell Maritime Press, Inc.)

cutter at the end of a ladder excavates the bottom sediment and guides it into the suction. The excavated material is picked up and pumped by a centrifugal pump to a designated disposal area through a 15 cm (6 in.) to 112 cm (44 in.)* pipeline as a slurry with a typical solids content of 10 to 20 percent by weight. The nominal size of the dredge is usually defined by the diameter of its discharge pipeline. For conventional

* Pipeline sizes are given in terms of centimetres and inches for the convenience of the reader.

cutterhead dredges the diameter of the cutter is approximately three to four times the diameter of the suction pipe. The typical cutterhead dredge is swung in an arc from side to side by alternately pulling on port and starboard swing wires connected to anchors through pulleys mounted on the ladder just behind the cutter. Pivoting on one of two spuds at the stern, the dredge "steps" or "sets" forward (Figure 3). Although the cost of mobilizing a cutterhead dredge is relatively high, its operation is nearly continuous and production rates (i.e., cubic metres of material dredged per hour) are generally high.[15,21]

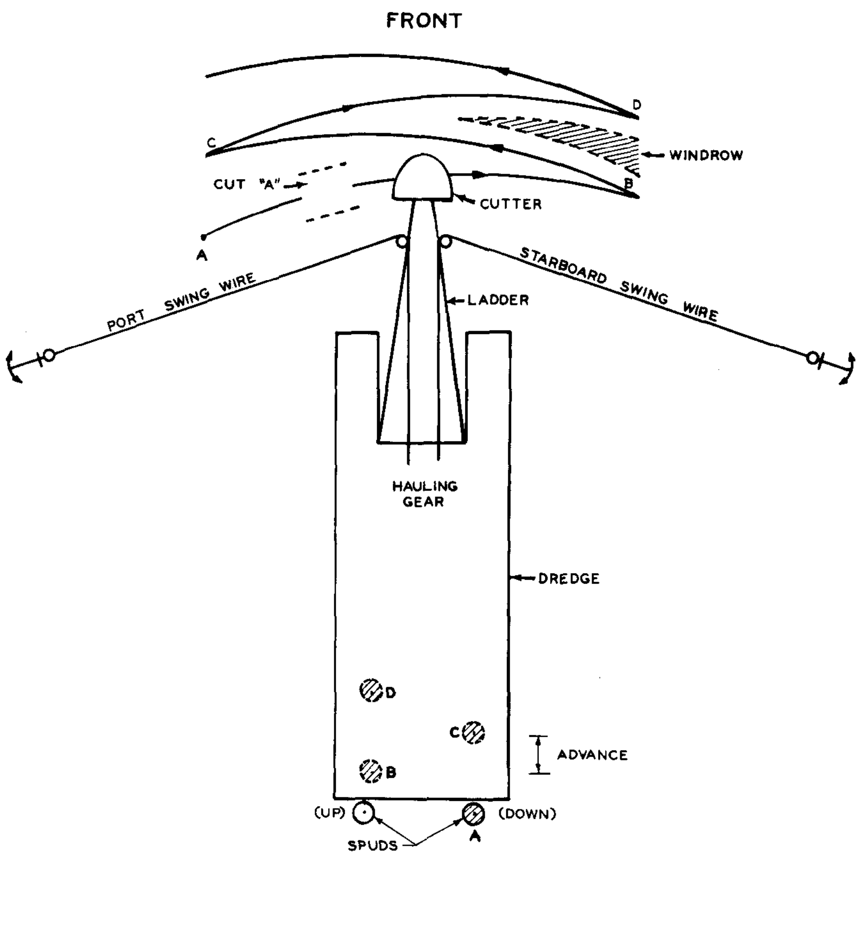

Figure 3. Typical (stabbing) method for operating a cutterhead dredge (Adapted from Reference 27. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

Sources of turbidity

25. Most of the turbidity generated by a cutterhead dredging operation (exclusive of disposal) is usually found in the vicinity of the cutter.[22] The levels of turbidity are directly related to the type and quantity of material cut, but not picked up by the suction. The amount of material supplied to the suction is controlled primarily by the rate of cutter rotation, the vertical thickness of the dredge cut, and the swing rate of the dredge (i.e., the horizontal velocity of the cutter moving across the cut). The ability of the dredge's suction to pick up this bottom material determines the amount of cut material that remains on the bottom or suspended in the water column. In addition to the dredging equipment used and its mode of operation, turbidity may also be caused by sloughing of material from the sides of vertical cuts, inefficient operational techniques, and the prop wash from the tenders (tugboats) used to move pipeline, anchors, etc., in the shallow water areas outside the channel. These factors will be discussed in more detail in the following paragraphs.

Field measurements

26. Although a properly designed cutter will efficiently cut and guide the bottom material toward the suction, the cutting action and turbulence associated with the rotation of the cutter will resuspend a portion of the bottom material being dredged. Excessive cutter rotation rates tend to propel the excavated material away from the suction pipe inlet.

a. Turbidity levels around a 61-cm (24-in.) cutterhead dredge excavating fine-grained maintenance material from Mobile Bay ship channel were elevated above background levels of 25 to 30 mg/ℓ only within 1.5 m of the bottom. Near-bottom levels of up to 125 mg/ℓ occurred approximately 300 m in front of the cutterhead; a value of 336 mg/ℓ was recorded 30 m behind the cutter.*

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* Personal Communication, 7 October 1977, Maynard M. Nichols, Associate Professor, Virginia Institute of Marine Science, Gloucester Point, Va.

b. Near-bottom suspended solids levels within 2 m of the cutter of a 69-cm (27-in.) cutterhead dredge widening a portion of the Corpus Christi ship channel (i.e., new work) ranged from background concentrations to 580 mg/ℓ relative to "background" levels of 39 to 209 mg/ℓ measured 73 m to the side of the dredge.[22]

c. Levels of suspended solids under low current conditions (i.e., less than 5 cm/sec) near the cutter of a 61-cm (24-in.) cutterhead dredge excavating fine-grained (new work) material from depths of 6 to 12 m in Yokkaichi Harbor ranged from 2 mg/ℓ to 31 g/ℓ, 1 mg/ℓ to 16 g/ℓ, and 1 mg/ℓ to 4 g/ℓ at distances of 1, 2, and 3 m above the cutter, respectively, relative to background levels of 1 to 18 mg/ℓ. Average turbidity levels appeared to decrease exponentially from the cutter to the water surface. In addition, 60 m in front of the cutter turbidity levels in the near-surface water ranged from 1 to 17 mg/ℓ, whereas near-bottom levels ranged from 5 to 205 mg/ℓ.[23]

27. Based on these limited field data collected under low current conditions, elevated levels of suspended material appear to be localized to the immediate vicinity of the cutter as the dredge swings back and forth across the dredging site. Within 3 m of the cutter suspended solids concentrations are highly variable, but may be as high as a few tens of grams per litre; these concentrations decrease exponentially from the cutter to the water surface. Near-bottom suspended solids concentrations may be elevated to levels of a few hundred milligrams per litre at distances of a few hundred metres from the cutter. This led Yagi et al.[23] to conclude that "in the case of steady dredging of a thin sedimented mud layer, the effect of dredging on turbidity was found to be almost imperceptible at locations several tens of metres distance from the cutter."

Turbidity generation vs. operational conditions

28. As previously indicated, the levels of turbidity found near the cutter depend primarily on the type and amount of material that is excavated, but not drawn into the dredge's suction. This "residual" material may remain in suspension or may settle into the existing cut where it again becomes susceptible to resuspension by ambient currents and turbulence generated during subsequent cuts. Analysis of the data collected in Yokkaichi Harbor indicates that as the amount of this

residual material increases, the turbidity levels around the cutter apparently increase exponentially.[23] According to calculations made by Yagi et al.,[23] the amount of residual material increases as the swing rate increases. Further examination of these data (by this author) also indicates that in most cases the amount of residual material generally increases as the thickness of the cut increases. Consequently, as the thickness of the cut and swing rate increases, the turbidity levels generated by the operation increase exponentially. There is also a similar relationship between turbidity generation and the rate of cutter rotation.[22]

29. The levels of turbidity in the vicinity of the cutter are apparently not only dependent on the operation of the dredge during a particular cut, but are also related to the amount of material remaining in suspension from the previous cut(s). In fact, during the first four swings of the dredging operation monitored by Yagi et al.,[23] the levels of turbidity around the cutter increased with each successive cut. This trend of increasing levels of suspended solids around the cutter probably continues until a quasi-steady state condition is reached when the amount of material resuspended by the cutter is equal to the amount of material that settles to the bottom.

30. Because the production rate of a dredge is so closely linked with its operation (i.e., thickness of the cut, swing rate, cutter rotation rate, etc.), the levels of turbidity around the cutter may be directly related to the dredge's production rate. This relationship is supported by data (from Yagi et al.[23]) plotted for fine-grained material in Figure 4 showing the levels of suspended solids 1 m from the cutter of a 61-cm (24-in.) cutterhead dredge vs. the production of the dredge (relative to its apparent maximum production rate) during the fourth cut on 26 test runs. Although the scatter in the data is great, there is a general trend showing increasing turbidity levels 1 m from the cutter with increasing rates of relative production. However, there is apparently no well-defined upper limit to the amount of turbidity that the cutter can generate. Yet, the data within the shaded region

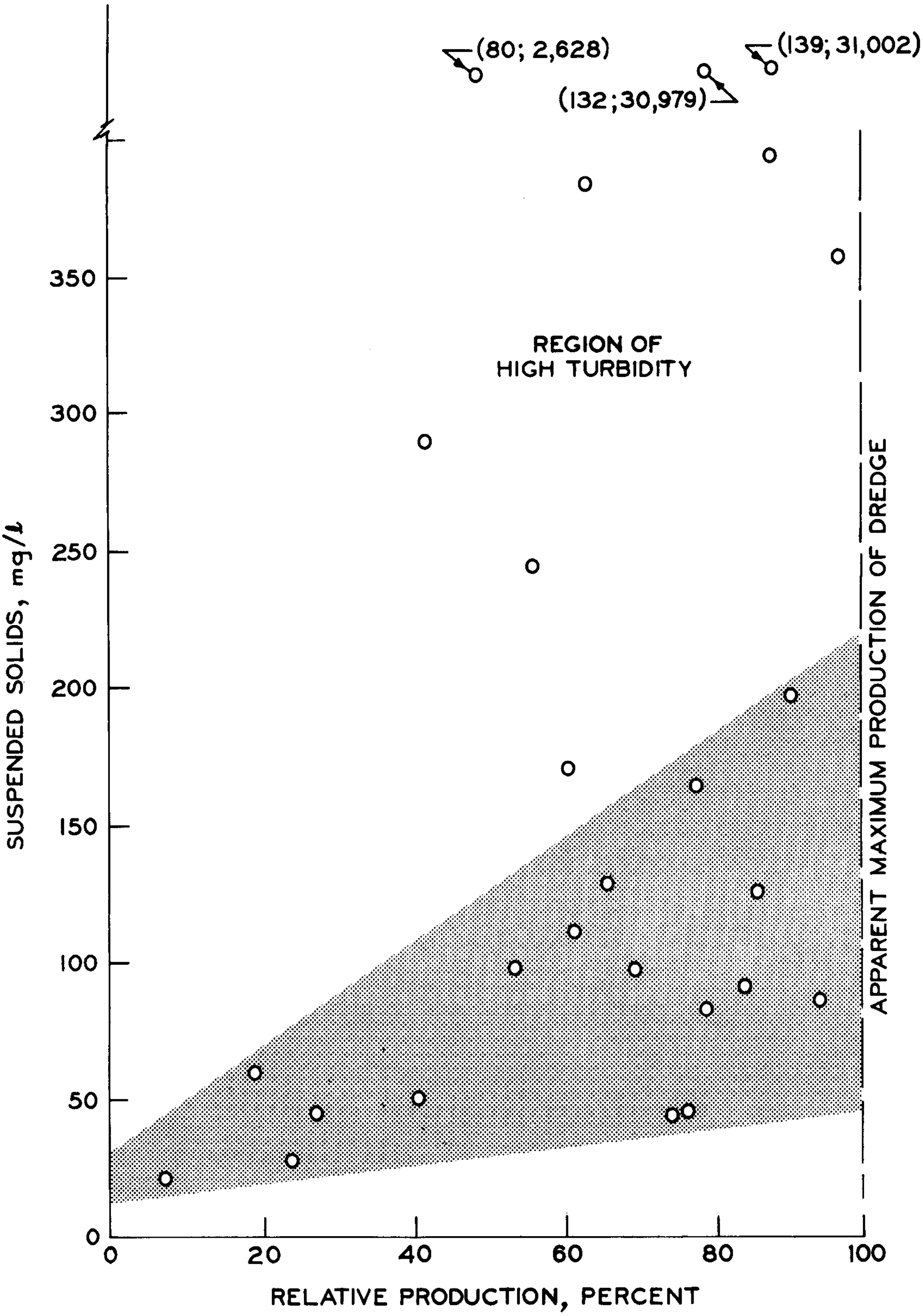

Figure 4. Relationship between the concentration of suspended solids 1 m from the cutter and the relative production of a 61-cm (24-in.) cutterhead dredge

(Figure 4) indicate that it is possible to increase the rate of a dredge's production up to its maximum rate (dotted line, Figure 4) without generating excessive levels of turbidity. Using high swing rates, large cuts, or high cutter rotation rates not only resuspends large amounts of dredged material, but also may lead to high levels of solids in the slurry, which may plug the pipeline.

31. To summarize, the turbidity generated around the cutter of a cutterhead dredge apparently increases exponentially as the thickness of the cut, rate of swing, and cutter rotation rate increase. Although suspended solids levels around the cutter also increase with increasing rates of production, it is possible to maximize the production rate of the dredge without resuspending excessive amounts of bottom sediment. These general relationships should be characteristic of all cutterhead dredging operations; however, the levels of turbidity generated will, of course, depend on the size and characteristics of the dredge, the sediment type, and the environmental and operational conditions.

Turbidity control

32. Cutter design. The design of a cutter depends primarily on the characteristics of the dredge on which it is used, the effective dredging depth, and the type of material being excavated. Among the various factors that must be considered when selecting a cutter are the number of cutter blades, the twist or curl of the blades, and the shape of the cutter relative to the length of the ladder and the depth of the project. For example, a cutter designed to dig at 10 m will not be as effective at 20 m, if used on the same ladder. Using an improperly designed cutter often requires thicker cuts to provide the suction with an adequate supply of material, thereby generating excessive levels of turbidity. Therefore, the cutter should be selected based on the requirements of a particular project.[22]

33. In an effort to maximize the efficiency of the cutter, several United States and foreign dredge manufacturers are developing and refining new cutter designs. In particular, the Canadian Government has developed a conical cutter, which apparently has a lower rim speed relative

to the typical basket cutter and may reduce the levels of cutter generated turbidity. Additional analyses of turbidity generation as a function of dredge production are now being performed.*

34. Cutter removal. In some cases where the material will flow naturally (i.e., noncohesive materials), the efficiency of the dredging operation can be increased by removing the cutter altogether. Since the suction can then be placed closer to the loose material, the suction's pickup capability increases and the dredge's production rate should improve; the amount of turbidity generated would also be reduced because there is no rotating cutter.[22]

35. Suction. The dredge's suction (Figure 2), which picks up the material that has been cut, can be partially responsible for turbidity generation around the cutter if the energy (i.e., head) provided to the suction by the dredge pump is not great enough to pick up all of the material disturbed by the cutter. In this situation, water-jet booster systems or ladder-mounted submerged pumps can be installed on cutterhead (or hopper) dredges at a considerable cost to increase the energy available for carrying the material and maintaining an adequate slurry velocity in the suction. This will enhance the dredge's pickup capability, increase the slurry density and potential production rate, and should decrease the generation of turbidity.[23,24]

36. Cutter-suction combination. On a typical cutterhead dredge, the cutter is turned by the cutter shaft; the suction pipe is mounted below the shaft. With this arrangement, the cutter must have a diameter that is approximately three to four times the diameter of the suction pipe. However, a new dredge may be designed so that the cutter is attached directly to the suction pipe and turned by the rotation of the suction pipe instead of the cutter shaft. According to Huston and Huston,[22] this system has several advantages. The size of the cutter can be reduced to about twice the diameter of the suction. This not only will increase the amount of force on the cutter blades without any

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*Personal Communication, 18 May 1978, C. G. Benckhuysen, Chief, Marine Equipment, Marine Directorate, Public Works, Canada, Ottawa, Ontario, Canada.

increase in the horsepower of the cutter motor, but also will reduce the distance between the suction mouth and the material being dredged. In addition, the shape of the suction will more closely approximate the ideal bell-shaped mouth, thereby reducing the amount of energy lost as the material enters the suction mouth. Finally, the cutter will more effectively feed material into the suction from the top, sides, and bottom rather than just from the bottom. Although all of these factors tend to enhance the pickup efficiency of the dredge and thereby reduce the amount of material subject to resuspension during an operation, the cutter-suction combination is rarely incorporated into new dredge designs.

37. Dredge production and efficiency. The profitability of a dredging operation depends largely on the production rate of the dredge itself; high production rates mean higher profits. However, where turbidity generation may be a potential problem, those operational parameters (e.g., cutter rotation rate, swing rate, and thickness of cut) affecting the generation of turbidity must be controlled relative to the dredge's production. Unfortunately, it is difficult to instantaneously measure a dredge's rate of production. Normally, the dredge operator or leverman can get some indication of production rate from the dredge's vacuum and pressure gauges. But these readings do not indicate slurry density or velocity, both of which are needed to determine the production rate of the dredge. By installing a production metering system,[25,26] production rate can be closely monitored relative to the dredge's operation. In addition, the manufacturers claim that these metering systems can improve production rates by 10 to 30 percent depending on the skill and experience of the leverman.

38. The method of swinging the dredge can also affect the dredge's production rate. Using a simple "stabbing" method (Figure 3), the dredge swings to the right with the starborad spud down and the port spud raised off the bottom. At the end of the cut, the port spud is lowered, the starborad spud raised, and the dredge swings to the left. In this manner the dredge swings from side to side and advances down the channel cutting a zigzag pattern of arcs leaving some areas undredged (i.e., windrows, Figure 3), and covering other areas twice at the end of

the swing. This method of advancing the dredge can be modified and the production rate increased substantially by using a spud carriage system (Figure 5)[27] or Wagger system (Figure 6),[28] which allow the dredge to advance to the end of each cut, thereby sweeping the cutter in a pattern of concentric arcs over the dredging site. With the spud carriage system the working spud is not permanently fixed to the dredge, but is mounted on a hydraulically powered carriage that moves along a slot at the stern of the dredge. The dredge advances as the working spud moves from position A to D (Figure 5); the walking spud at the stern is then dropped and the working spud is raised and repositioned at A. The Wagger system (Figure 6), developed by Daleeter Corporation, Lansing, Mich.,* consists of two pontoons linked by a steel truss and anchored by three spuds. A second truss that is connected to the stern of the dredge slides back and forth on top of the truss/pontoon section. By expanding and contracting the Wagger with hydraulic rams, the dredge advances over the dredging area. The point of connection between the upper truss and the dredge acts as a pivot point around which the dredge swings. The Wagger also eliminates the need for swing wires.

39. The efficiency of an operation can also affect its profitability. An inefficient operation can result in lower production rates, longer dredging operations, as well as excessive levels of turbidity. In addition to a well-designed dredging system, the efficiency of an operation can be improved by using other accessory equipment that has been developed over the last several years. Among these is the Hofer system that maintains the slurry velocity in the suction when the solids content becomes excessive. This prevents plugging of the pipeline and the costly delays that often result.[22] The efficiency and production of a dredge can also be enhanced by installing a gas removal system on the suction to remove any naturally generated gas from the dredged material slurry before it reaches the main pump.[15] Swell compensators and articulated ladders are also available for maintaining

* For more information contact Mr. Lee Smith, Lee Power Equipment, Inc., Remus, Mich., 49340, 517-561-2270

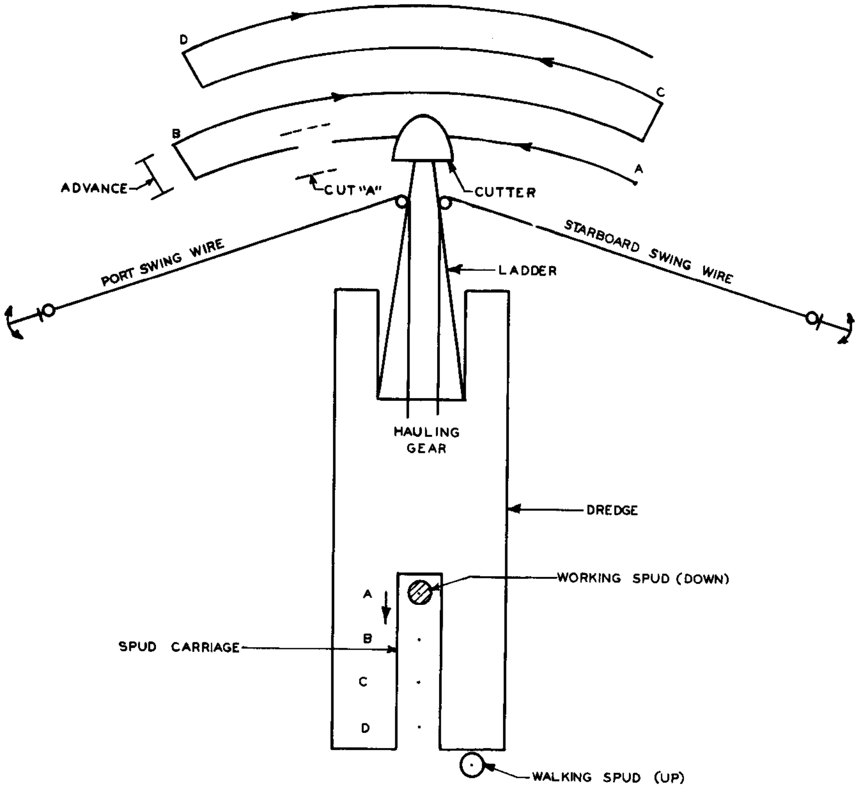

Figure 5. Cutterhead dredge with a spud carriage system (Adapted from Reference 27. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

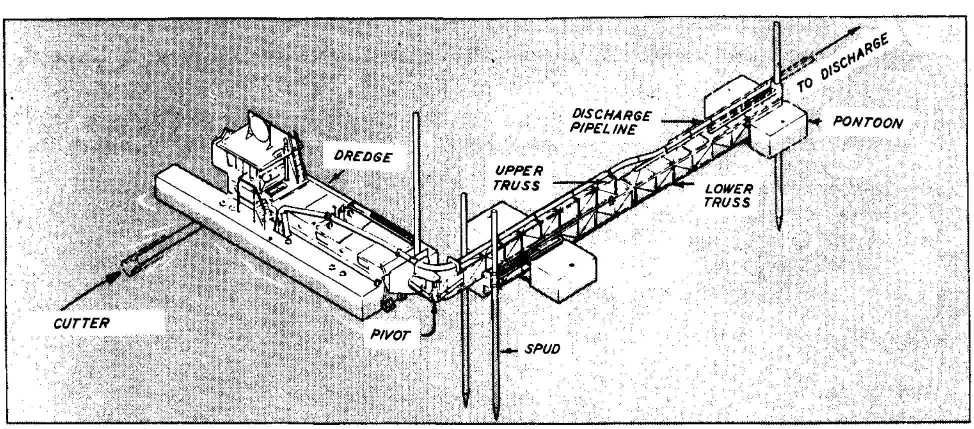

Figure 6. Wagger system. (Patent rights owned by Lee Power Equipment, Inc. Figure used through courtesy of Mr. Leward N. Smith.)

cutter contact with the bottom sediment in rough water. Electronic systems are also available for controlling the dredge's swing, cutter speed, etc., as well as indicating swing force, cutter force, ladder angle, swing angle, and dredging depth.[29,30] Automatic microwave or laser positioning systems[31] and gyro compasses can also provide assistance in maintaining accurate positioning of the dredge. Although this equipment can increase the overall efficiency of the dredging operation and aid in reducing the amount of turbidity generated, it does not eliminate the need for a qualified leverman to control the overall dredging operation. Unfortunately, at this time there is no formal course of instruction for training dredge personnel in the practical aspects of dredging.

40. Operational procedures.[22] Even when the most advanced dredging equipment is used, if it is not used effectively, its potential for increasing production and minimizing turbidity generation is greatly reduced. Therefore, the leverman's techniques for operating a dredge are of utmost importance:

a. Large sets and very thick cuts should be avoided, since they tend to bury the cutter and may cause high levels of turbidity if the suction cannot pick up all of the dislodged material.

b. The leverman should swing the dredge so that the cutter will cover as much of the bottom as possible. This minimizes the formation of windrows or ridges of partially disturbed material between the cuts (Figure 3); these windrows will tend to slough into the cuts and may be susceptible to resuspension by ambient currents and turbulence caused by the cutter. Windrow formation can be eliminated by swinging the dredge in close, concentric arcs over the dredging area. This may involve either modifying the basic stepping methods used to advance the dredge or using a Wagger or spud carriage system.

c. Side slopes of channels are usually dredged by making a vertical "box cut"; the material on the upper half of the cut then sloughs to the specified slope. The specified slope should be cut by making a series of smaller boxes. This method, called "stepping" the slope, will not eliminate all sloughing, but will help to reduce it.

d. On some dredging projects it may be more economical to roughly cut and remove most of the material, leaving a relatively thin layer for final cleanup after the project has been roughed out. This remaining material may be subject to resuspension by ambient currents or prop wash from passing ship traffic.

e. When "layer cutting" is used, the dredge will remove a single layer of material over a large portion of the channel; the dredge is then set back to dredge another layer. This continues down to the required depth of the project. Since loose material is often left on the bottom after each layer is dredged, this technique should only be used where resuspension of the remaining material will not create serious problems.

f. The prop-wash from the tenders (i.e., tugboats) used to move anchors, sections of pipeline, barges, and the dredge itself can resuspend a great deal of bottom material, especially in shallow water adjacent to the channel. Although prop-wash cannot be eliminated, oversized tenders should not be used in shallow water areas.

g. In addition to prop-wash, significant resuspension of bottom material often occurs when the anchors used in support of the operation are dragged along the bottom when the dredge is moved to a new location. Anchor dragging should be avoided.

h. During the course of a typical operation, the length of the pipeline may have to be adjusted by adding or removing sections. Before the pipeline is broken it should be flushed thoroughly with water, not only to prevent clogging of the pipeline when pumping is resumed, but also to maintain low turbidity levels around the pipeline. Obvious leaks from poorly sealed ball joints between pipeline sections should also be repaired.

Hopper Dredges

41. In those areas characterized by heavy ship traffic or rough water, a self-propelled hopper dredge will probably be used. During a hopper dredge operation, as the dredge moves forward, the bottom sediment is hydraulically lifted from the channel bottom through a draghead, up the dragarm (i.e., trailing suction pipe), and temporarily stored in hopper bins in the ship's hull. Most modern hopper dredges have one or two dragarms mounted on the side of the dredge and have storage capacities ranging from several hundred to over 9000 cu m. The hoppers are either emptied by dumping the dredged material through doors in the bottom of the ship's hull or by direct pumpout through a pipeline.[15,21]

Sources of turbidity

42. Resuspension of fine-grained maintenance dredged material during hopper dredge operations is caused by the dragheads as they are pulled through the sediment, turbulence generated by the vessel and its prop wash, overflow of turbid water during hopper filling operations, and dispersion of dredged material during open-water disposal. This latter source of turbidity is discussed in great detail in the DMRP report entitled "Field Study of the Mechanics of the Placement of Dredged Material at Open-Water Disposal Sites."[7] Only the turbidity generated during the dredging operation will be discussed here.

43. The most obvious source of near-surface turbidity is the overflow water. During the filling operation dredged material slurry is often pumped into the hoppers after they have been filled in order to maximize the amount of higher density material in the hopper. The lower density, turbid water at the surface of the filled hoppers overflows and is usually discharged through ports located near the waterline of the dredge. Distributions of suspended solids in these overflow plumes are primarily dependent on the nature of the sediment being dredged; the design and operation of the dredge (such as forward speed and pumping rate); the nature, concentration, and volume of overflowed material; the locations of the overflow ports; and the hydrologic characteristics of the dredging site (such as water depth, salinity, and current direction and velocity). Although there may be no increase in the hopper load achieved by continued pumping of fine-grained sediment into filled hoppers,[32,33] overflowing is a common practice.

Field measurements

44. Measurements of suspended solids concentrations in the vicinity of the hopper dredge CHESTER HARDING during a maintenance operation in San Francisco Bay indicated that a near-bottom turbidity plume of suspended dredged material extended up to 700 m downcurrent from the dredge.[16] In the immediate vicinity of the dredge a well-defined, upper plume was generated by the overflow process and a near-bottom plume by draghead resuspension; 300 to 400 m behind the dredge the two plumes merged into a single plume (Figure 7). As the distance from the

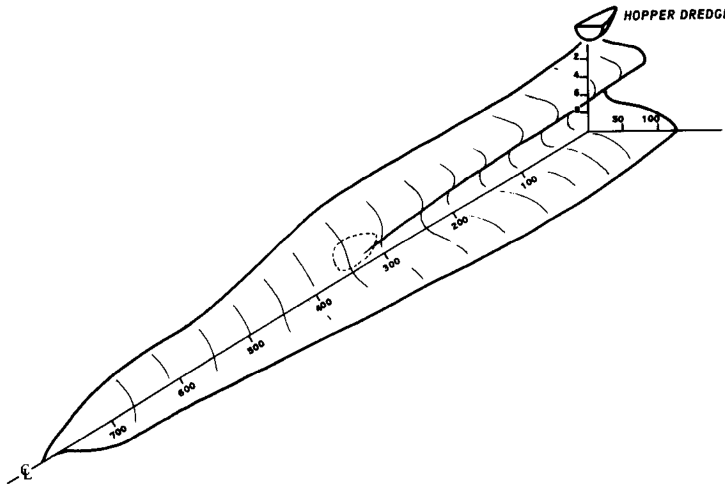

Figure 7. Hypothetical suspended solids plume downstream of a hopper dredge operation with overflow in San Francisco Bay. All distances in metres

dredge increased, the suspended solids concentrations in the plume generally decreased and the plume became increasingly limited to the near-bottom waters, although some surface discoloration was often evident along the entire length of the plume. Suspended solids concentrations in the upper and midwater column rarely exceeded several hundred milligrams per litre (relative to background concentrations of 31 to 35 mg/ℓ) except directly adjacent to the hopper dredge overflow ports where concentrations were as high as several grams per litre. Near-bottom plume concentrations were usually less than a few grams per litre relative to background concentrations of 38 to 123 mg/ℓ.

45. Near-surface suspended solids concentrations were also measured in the overflow plumes generated during maintenance operations by the MARKHAM in Saginaw Bay ship channel, Lake Huron,[34] and the GOETHALS in the Thimble Shoal Channel, Chesapeake Bay.[35] These plume measurements are summarized in Figure 8. In addition to the obvious exponentially decreasing levels of suspended solids with increasing distance from the dredge, the width of the near-surface plume behind the GOETHALS

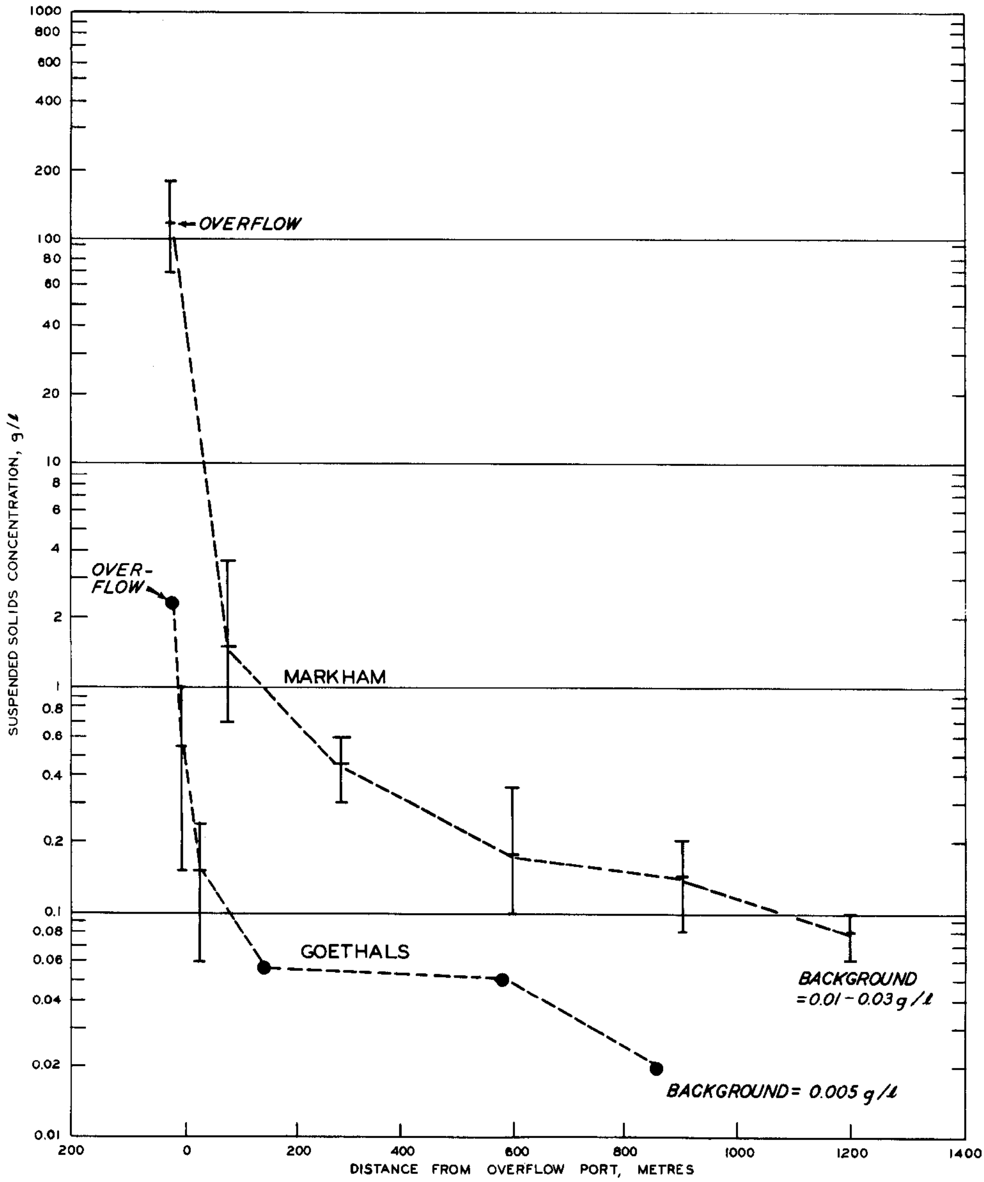

Figure 8. Relationship between concentration of suspended solids in the near-surface overflow plume and the distance (in metres) downstream of the overflow ports

increased with increasing distance from the dredge. This surface pattern resulted from lateral dispersion of the dredged material and attained a half-width of approximately 75 m at a distance of 900 m behind the dredge.

46. These data indicate that the suspended solids levels generated by a hopper dredge operation are primarily caused by hopper overflow in the near-surface water and draghead resuspension in near-bottom water. Suspended solids concentrations may be as high as several tens of grams per litre near the discharge port and as high as a few grams per litre near the draghead. Turbidity levels in the near-surface plume appear to decrease exponentially with increasing distance from the dredge due to settling and dispersion, quickly reaching concentrations less than 1 g/ℓ. However, plume concentrations may exceed background levels even at distances in excess of 1200 m.

Turbidity control

47. Operational procedures. Examination of Figure 8 suggests that the levels of suspended solids in a plume generated by typical hopper dredge overflow can be decreased by reducing the solids concentration of the overflowed material. This can be accomplished by reducing the flow rate of the slurry being pumped into the hoppers during the latter phases of the hopper filling operation.[33] By using this technique, the solids content of the overflow can be decreased substantially (e.g., from 200 to 100 g/ℓ or less by weight[34]), while the loading efficiency of the dredge is simultaneously increased.

48. Flocculant injection. There have been several attempts made to increase the rate at which dredged material settles in the hoppers and simultaneously decrease the solids content of the overflow by injecting flocculants into the slurry prior to discharge into the hoppers or spraying flocculants into the filling hoppers.[36,37] Whereas these techniques are ineffective due primarily to the high solids content of the slurry, the settling rate of the suspended material in the overflow water may be increased somewhat by injecting polyelectrolytes (flocculants) into the overflow water before it is discharged overboard. During tests in Saginaw Bay ship channel, Lake Huron, polyelectrolytes were used to treat the overflow from the hopper dredge MARKHAM that had

a typical solids content of 100 g/ℓ or less. Average near-surface suspended solids concentrations in the plume at a distance of 1350 m from the dredge's overflow ports averaged 58 mg/ℓ (relative to average background concentrations of 24 mg/ℓ) and 36 mg/ℓ (relative to background values of 29 mg/ℓ) for untreated and treated conditions, respectively. Based on these data, treatment of the overflow may provide a marginal increase in the settling rate of the solids suspended in the overflow plume, thus reducing the levels of near-surface turbidity during hopper dredge overflow. For the dredging operation described above, the cost of flocculant addition per 10 cu m of overflow was approximately $0.24.[34]

Submerged overflow system

49. To minimize the dispersion of the discharged overflow the Ishikawajima-Harima Heavy Industries Company, Ltd., Japan, in cooperation with Tokushu-Shunsetsu Company, Ltd., Japan, has developed a relatively simple submerged discharge system for hopper dredge overflow.[38] The overflow collection system in the dredge was streamlined to minimize the incorporation of air bubbles and the overflow discharge ports were moved from the sides to the bottom of the dredge's hull. With this arrangement, the slurry descends rapidly to the bottom with a minimum amount of dispersion within the water column.

50. This modified overflow system has been successfully used on three Japanese trailing hopper dredges with capacities ranging from 2000 to 4000 cu m without generating any significant near-surface turbidity in the vicinity of the dredge. Suspended solids concentrations around a 2000 cu m hopper dredge with a conventional overflow system ranged from 10 to 1990 mg/ℓ above average ambient concentrations of 8 mg/ℓ, whereas with the submerged system solids concentrations were at most only 5 mg/ℓ above ambient levels of 7 mg/ℓ. The system can be incorporated into existing hopper dredges, hopper barges, and scows through simple modification of existing overflow systems. Symcon Marine Corporation (P.O. Box 1800, San Pedro, Calif. 90733) currently has the marketing franchise for this antiturbidity system in the United States.

Agitation Dredging

51. Agitation dredging is often used in some parts of the country to deepen shallow channels or clean out low-density material from slips in harbor areas.[39] When this "dredging" technique is used, the bottom material is intentionally resuspended by prop wash,[40] dragging the bottom,[41] continuous hopper dredge overflow, or sidecasting.[42] The material is then transported downstream with the river current or outgoing tidal flow. Although this type of operation can be quite effective and economical, its use should be restricted to those areas where short-term exposure to high levels of suspended solids will not be detrimental.

Unconventional Dredging Systems

52. Over the last few years several unconventional dredging systems have been developed in the United States and overseas to pump dredged material slurry with a high solids content and/or to minimize the generation of turbidity. Although an evaluation of their potential for reducing the generation of turbidity was beyond the scope of this study, seven unconventional systems are briefly described. Most of these systems are not intended for use on typical maintenance operations; however, they may provide alternative methods for unusual dredging projects (e.g., chemical "hot spots") when the capabilities of a particular system provide some advantage over conventional dredging equipment.

Mud Cat

53. The Mud Cat (Mud Cat Division, National Car Rental System, Inc., P. O. Box 16247, St. Louis Park, Minn. 55416) is a relatively small, portable hydraulic dredge designed for projects where a 38- to 92-cu m/hr discharge rate is sufficient. Instead of the conventional cutter the Mud Cat has a horizontal cutterhead equipped with cutter knives and a spiral auger that cuts the material and moves it laterally toward the center of the auger where it is picked up by the suction (Figure 9).

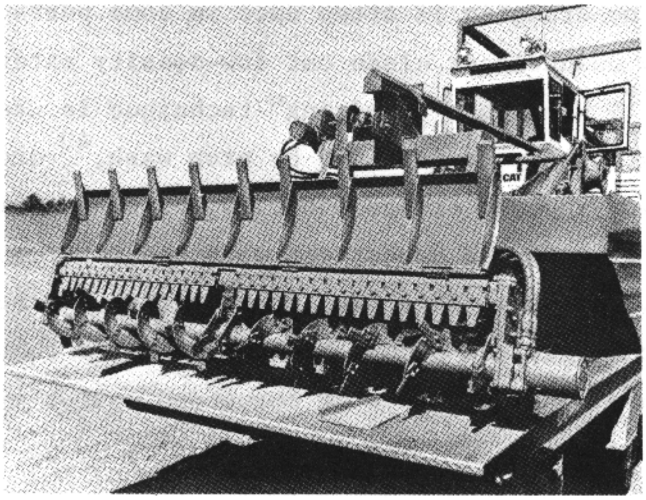

Figure 9. Horizontal cutterhead of the Mud Cat dredge showing cutter knives and spiral auger (Courtesy of MUDCAT Division National Car Rental Systems, Inc.)

This cutter can remove a layer of material 2.4 m wide and 0.4 m thick from water depths of 0.6 to 4.5 m leaving the dredged bottom flat and free of the windrows that are characteristic of the typical cutterhead dredging operation.

54. By covering the cutter/auger combination with a retractable mud shield the amount of turbidity generated by the Mud Cat's operation can be minimized. During one operation near-bottom suspended solids concentrations 1.5 m from the auger were usually slightly greater than 1 g/ℓ, relative to near-bottom background concentrations of 500 mg/ℓ. Surface and middepth concentrations measured 1.5 to 3.0 m in front of the auger were typically less than 200 mg/ℓ above background values of 40 to 65 mg/ℓ. In general, the turbidity plume was confined to within 6 m of the dredge.[43]

Waterless dredge

55. Waterless Dredging Company (124 North 15th Street, Mattoon, Ill. 61938) has recently developed a dredging system where the cutter and a submerged centrifugal pump are enclosed within a half-cylindrical shroud. By forcing the cutterhead into the material, the cutting blades remove

the material near the front of the cutterhead with little entrainment of carrier water. According to the manufacturer, this system apparently is capable of pumping slurry with a solids content of 30 to 50 percent by weight with little generation of turbidity. Dredge (pipeline) sizes range from 15 to 30 cm.*

Delta dredge

56. Delta Dredge and Pump Corporation (11743 Lackland Road, St. Louis, Mo. 63141) has also developed a small portable dredge that apparently removes material at a high solids concentration using a submerged 30-cm (12-in.) pump coupled with two counter rotating, low speed, reversible cutters (Figure 10). According to the manufacturer, this equipment is capable of making a relatively shallow 2.3-m-wide cut without disturbing the surrounding material. For this reason, turbidity levels in the vicinity of the cutterhead are apparently low.[44]

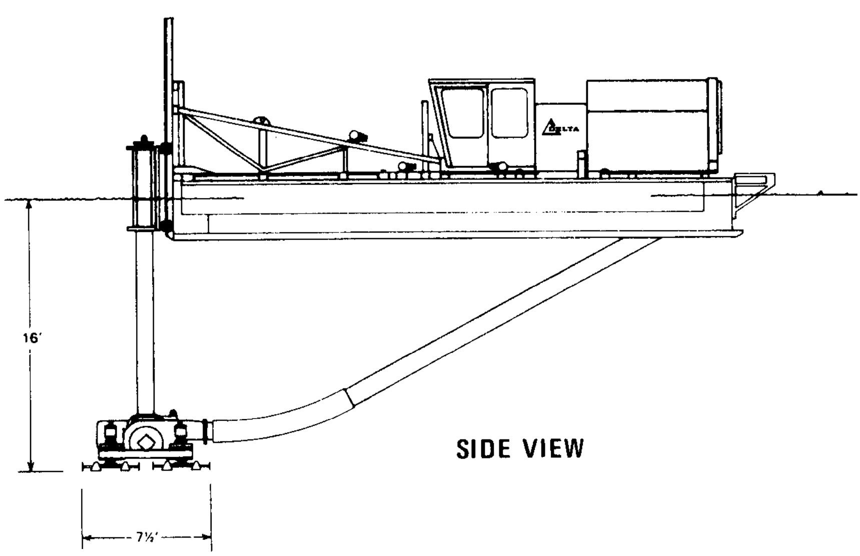

Figure 10. Delta dredge (Taken from Reference 44. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

* Personal Communication, 17 October 1977, Don Searles, Waterless Dredging Company, Mattoon, Ill.

Bucket wheel dredge

57. Ellicott Machine Corporation (Baltimore, Md.) has recently developed a unique bucket wheel excavator (Figure 11) as a means of improving the efficiency of the cutting operation. Because the cutting force is concentrated on a much shorter cutting edge, the bucket wheel has the capability of efficiently digging highly consolidated material. In addition, the material is force fed to the suction as the wheel turns, making it possible to control the solids content of the dredged material slurry by varying the rotation speed of the wheel. Theoretically, this bucket wheel not only accurately digs to a prescribed level, but also maximizes the pickup of the excavated material.[27]

Pneumatic pumping systems

58. Pneuma. The Pneuma system,[45,46,47] developed by SIRSI (Italian Corporation for the Research of Water Use), Florence, Italy, was the first dredging system to use compressed air instead of centrifugal motion to pump slurry through a pipeline. Although it has been used extensively on European and Japanese dredging projects, the Pneuma

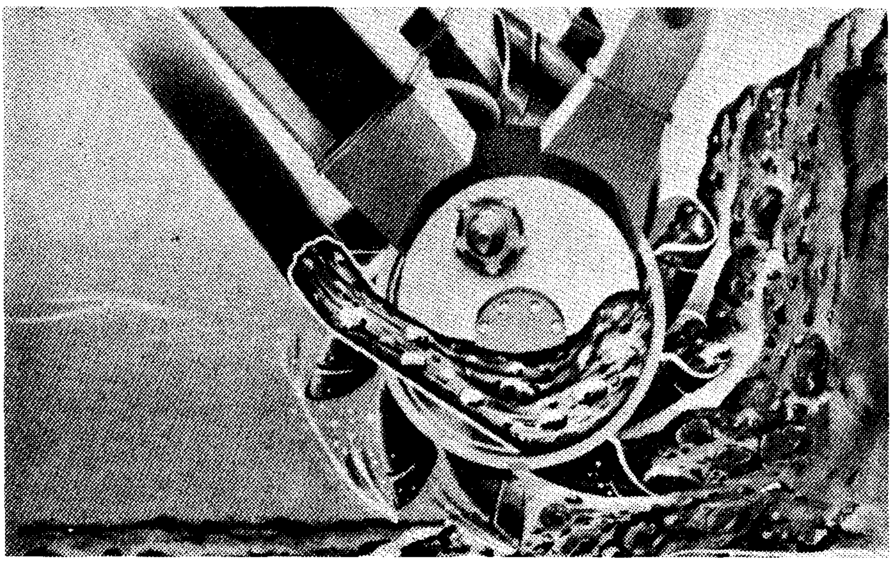

Figure 11. Bucket wheel dredge (Taken from Reference 27. Used courtesy of Symcon Marine Corp. and WODCON Assn.)

system has only been available in the United States since 1975 (through Pneuma North America, Inc., 823 Commerce Drive, Suite 230, Oak Brook, Ill.

60521). According to the literature published by the manufacturer, this system can pump a slurry with a relatively high solids content with little generation of turbidity.

59. The Pneuma system consists of a pump body (composed of three cylinders), compressor, shovel, and a distributor system that automatically controls the supply of compressed air to the cylinders. When the pump is submerged, sediment and water are forced into one of the empty cylinders through an inlet valve (Figure 12). After the cylinder is filled, compressed air is forced into the cylinder closing the inlet valve and simultaneously forcing the material out of an outlet valve and into the discharge line. When the cylinder is empty, the air pressure is reduced to atmospheric pressure, the outlet valve closes, and the inlet valve opens. The two stroke cycle is then repeated. The distributor system controls the cycling phases of all three cylinders so there is always one cylinder operating in the discharge mode.

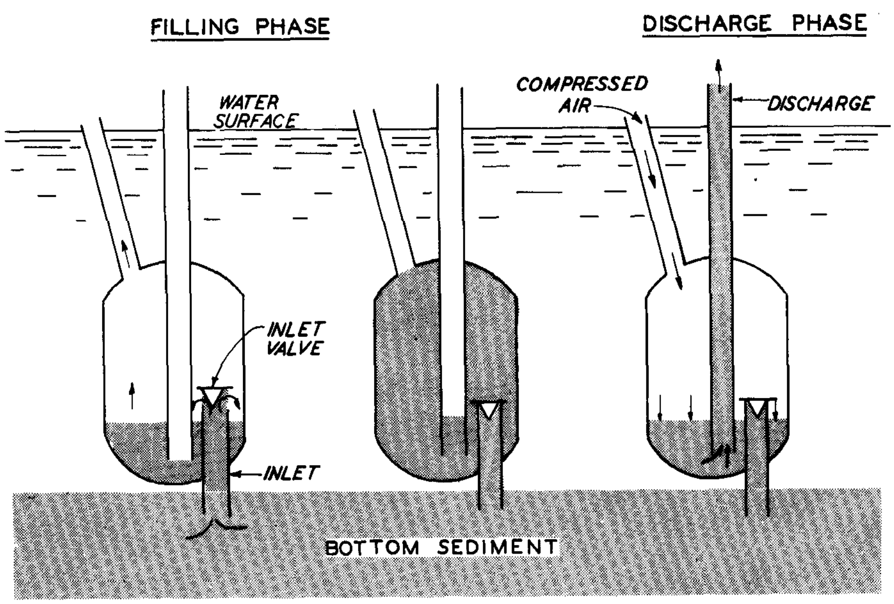

Figure 12. Operating principle of the pneumatic pump (Courtesy of Pneuma North America, Inc.)

60. Depending on the material being dredged and the mode of operation, the three cylinders of the Pneuma system can be arranged in various ways with different shovel attachments. The frontal shovels are

normally equipped with cutting grills that facilitate penetration into compact bottom sediment. The system has been used in water depths of 50 m; however, 100- to 200-m depths are theoretically possible. Depending on the size of the particular Pneuma pump used, production rates can range from 40 to 2000 cu m/hr. The pump can be deployed from a land-based or floating crane, pulled through the sediment in a trailing position, or attached to a dredging ladder.

61. According to unpublished data, the amount of resuspension generated by the Pneuma system is also apparently minimal.

a. During one maintenance dredging operation at the Port of Chofu, Shimonoseki, Japan, suspended solids levels of 4, 10, 26, and 48 mg/ℓ were measured at depths of 7, 4, 2, and 1 m above the bottom, respectively, approximately 5 m in front of a 300/60 Pneuma pump mounted on a ladder. Turbidity levels 30 m from the system appeared to remain within the general background range of 1 to 3 mg/ℓ.

b. During a second maintenance operation at Kita Kyushu City, Kokura, Japan, average turbidity levels measured 5 m from the ladder-mounted Pneuma pump were approximately the same as background values measured 50 to 100 m away. Only one turbidity measurement taken 1 m above the bottom, 5 m from the system, indicated an elevated value of approximately 13 mg/ℓ relative to background concentrations of 6 mg/ℓ.

62. Oozer. The Oozer pump,[48] developed by Toyo Construction Company, Ltd. (3-7-1 Kanda Nishikicho, Chiyoda-ku, Tokyo, Japan, and marketed in the United States by TJK, Inc., 7407 Fulton Avenue, N. Hollywood, Calif.), operates in a manner similar to that of the Pneuma system; however, there are two cylinders (instead of three) and a vacuum is applied during the cylinder-filling stage when the hydrostatic pressure is not sufficient to rapidly fill the cylinders. The pump is usually mounted at the end of a ladder and equipped with special suction heads and cutter units depending on the type of material being dredged. The conditions around the dredging system (i.e., the thickness of sediment being dredged, the bottom elevation after dredging, as well as the amount of resuspension) are monitored by high-frequency acoustic sensors and an underwater television camera. Based on production records, the larger Oozer system has an approximate dredging capacity ranging

from 300 to 500 cu m/hr. During one operation suspended solids levels within 3 m of the dredging head were all within background concentrations of less than 6 mg/ℓ. Dredging costs (excluding disposal) using the Oozer system are approximately $6 to $7/cu m.*

63. Mudlark. The Mudlark is another type of pneumatic pump that has been developed to transport dredged material. Similar to the Oozer, it has two chambers that are alternately phased; however, with this system compressed air drives a piston that pumps the slurry.

Clean Up system

64. To avoid the sediment resuspension typical of a cutterhead dredge, TOA Harbor Works (TOA Kensetsu Kogyo Company, Ltd., 5 Yobancho, Chiyoda-ku, Tokyo, Japan) has also developed a unique Clean Up system for dredging highly contaminated sediment.[49,50] The Clean Up head consists of a shielded auger that collects sediment as the dredge swings back and forth and guides it toward the suction of a submerged centrifugal pump (Figure 13). To minimize sediment resuspension, the auger is shielded and a movable wing covers the sediment as it is being collected by the auger. Any gas that is released from the sediment is trapped by a shroud and vented to the surface where it is collected. Sonar devices on both sides of the head indicate the elevation of the bottom in front of and behind the head; an underwater television system also indicates the amount of material being resuspended during a particular operation. During one dredging operation suspended solids concentrations around the Clean Up head ranged from 1.7 to 3.3 mg/ℓ at the surface and 1.1 to 7.0 mg/ℓ 3 m above the suction equipment relative to background near-surface levels of less than 4 mg/ℓ.

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* Personal Communication, 15 December 1977, Hyman Fine, Civil Engineer U. S. Army Engineer District, Norfolk, Norfolk, Va.

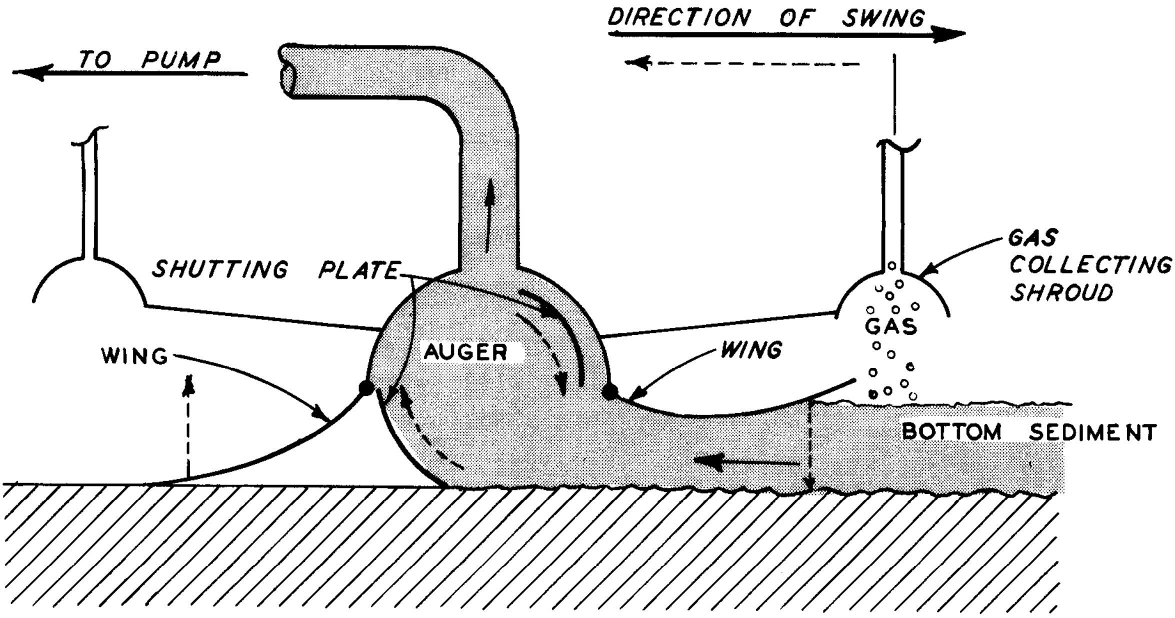

Figure 13. Cross-sectional view of the cutterhead of the Clean Up system (Redrawn from References 49 and 50. Used courtesy Symcon Marine Corp. and WODCON Assn.)

Dredge Selection

65. When considering an upcoming dredging operation, the project engineer may be faced with the problem of selecting the "best" dredge based on the cost and availability of different dredges, the operating conditions at the project site, the material to be dredged, the job specifications, and various environmental considerations.[51] According to a comparison of conventional dredges by Wakeman, Sustar, and Dickson,[52] "the cutterhead dredge seems to have the least effect on water quality during the dredging operation. This is followed by the hopper dredge without overflow. The clamshell dredge and hopper dredge during overflow periods both can produce elevated levels of suspended solids in the water column." Although this may be true under a given set of environmental conditions, the variability between different sites, material types, dredge sizes and capabilities, as well as perator performance and training makes it difficult to compare different types of dredges.

66. Unfortunately, since each dredging/disposal project is site specific, a dredge that may be ideal in one situation may not be suitable for another. The production rate of a given dredge relative to the levels of turbidity that may be generated, the duration of the project, and the background conditions should all be considered when evaluating the potential impact of different sizes and types of dredges. It is also important to remember that a sophisticated and expensive dredging system will not necessarily eliminate all environmental impacts associated with dredging operations. In addition, it is imperative to concurrently consider the compatibility of all the components of the dredging operation, including excavation, transportation, treatment, and disposal, as a total integrated system and not as separate components. The relative impact of each operation must be objectively evaluated relative to its cost and overall benefits.